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Shipbuilding docks as experimental systems for realistic assessments of anthropogenic stressors on marine organisms

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Shipbuilding docks as experimental systems for realistic assessments of anthropogenic stressors on marine organisms

Short title: Assessing realistic impacts of stressors

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Abstract

Empirical investigations of the impacts of anthropogenic stressors on marine organisms are typically performed under controlled laboratory conditions or via offshore experiments with realistic (but uncontrolled) environmental variation. Both approaches have merits, but laboratories generally fail to recreate natural environments or stressor-fields, and offshore studies are often compromised by confounding factors. We pioneered the use of a flooded shipbuilding dock to study realistic exposure to stressors and their impacts on intra- and interspecific responses of animals. Shipbuilding docks allow careful study of groups of known animals, including evaluation of their behavioral interactions, while enabling full control of the stressor and many environmental conditions. We showcase this approach for assessing impacts of pile-driving noise on fishes, and propose its use to study other anthropogenic stressors, including chemicals and ocean warming. Results from shipbuilding-dock studies could allow improved parameterization of predictive models relating to environmental risks and population consequences of anthropogenic stressors.

Introduction

The human population and associated industrial activity has greatly increased during recent decades, resulting in a rise in anthropogenic (man-made) pollution in terrestrial and aquatic environments. In the marine environment this has led to changes in the physicochemistry of our oceans. These changes include ocean warming (~0.11°C global water warming per decade of the top 75 m since 1971; IPCC 2014), increased seawater acidity (ocean surface water increased 0.1 pH units compared to pre-industrial levels; Raven et al. 2005), regional changes in ocean salinity as a consequence of global warming (>0.1 p.s.u. salinity increase in the top 500 m in high-evaporation regions in four decades in the Atlantic Ocean; Curry et al. 2003), and increased levels of ocean noise (e.g. 3.3 dB per decade since 1950 in the Northeast Pacific Ocean; Frisk 2012).

A range of human activities, including fossil-fuel consumption, resource extraction, construction, transportation and waste disposal generate pollution, and many of these activities and their potential impacts are expected to increase in the coming decades (Gattuso et al. 2015, Slabbekoorn Hans et al. 2010). Environmental stressors generated by human disturbance - hereafter referred to as 'anthropogenic stressors' - can impact negatively on marine organisms (e.g. Palstra et al. 2006) and some have been linked to population declines (Wada et al. 2013). Furthermore, impacts of marine contaminants can affect human health through consumption of fish from polluted waters (Foran et al. 2005). The increase in anthropogenic stressors in the oceans requires better understanding of impacts and consequences of current and predicted future stressor levels on marine organisms.

In this paper, we appraise the current methods used to study impacts of anthropogenic stressors on marine animals. We then introduce a novel approach – flooded shipbuilding docks – to studying impacts of man-made stressors on marine organisms and discuss merits and limitations of this approach compared to laboratory and offshore setups. We then showcase an example of dock usage to study impacts of anthropogenic noise on marine animals, evaluate strengths and weaknesses of this approach, and propose that a dock approach could be used to study impacts of other anthropogenic stressors on marine animals, including chemicals, eutrophication, salinity and ocean warming. Finally, we provide guidance on how to conduct such experiments using a dock setup, highlight opportunities and challenges, and propose questions this novel approach could be used to address.

Current empirical methods used to study impacts of anthropogenic stressors on marine animals

To date, our understanding of the impact of anthropogenic stressors on marine animals is derived from a combination of laboratory experiments and offshore studies. Here we compare these approaches and assess their merits and limitations (see Table 1 for a summary).

Laboratory experiments

Experiments conducted in laboratory conditions have been effective in testing potential impacts of a range of environmental stressors on individual organisms, including ocean warming (Scott and Johnston 2012) and ocean acidification (reviewed in: Fabry et al. 2008). Such studies have helped to decipher underlying mechanisms, identify stressor thresholds and have highlighted critical consequences of these stressors. Generally, laboratory studies allow for tight control of potential confounding factors and enable investigations that are difficult (or impossible) to carry out in the field. An example of this includes long-term studies performed under well-defined conditions. However, laboratory studies generally fail to capture environmental complexity (Taylor et al. 2015), are unlikely to recreate natural conditions of the 'stressor experience' (Slabbekoorn H. 2016), and typically use small aquaria (for the purpose of this paper an aquarium of 200 L is envisaged when comparing methods). Some of the greatest challenges for laboratory-based experiments are to assess impacts of stressors on individual phenotypes due to general phenotypic complexity, which can be influenced strongly, for example, by the social context; this is rarely accounted for in the laboratory. Additionally, stressors can also impact animals through disrupting interactions between individuals or between species, something rarely considered in the laboratory.

Offshore experiments using mesocosms

Studies that investigate impacts of anthropogenic stressors on animals in offshore locations, defined as any study located in the sea away from the shore, typically use mesocosms; an experimental system enclosing the study organisms. Such studies have showcased the possible impacts of several anthropogenic stressors, including ocean acidification (e.g. Kline et al. 2012) and chemicals (making use of existing contaminated locations: Berge and Brevik 1996). The main advantages of using mesocosms for offshore studies are that wild animals can be tested and investigated in their natural – albeit enclosed – environment, which potentially captures local physicochemical and biotic complexity. In addition, offshore mesocosms allow the study of stressors that are not possible to study without enclosures.

For example, investigating impacts of ocean acidification using small-scale (<2 m^3) enclosed units that can be placed upon the ocean floor (reviewed in Gattuso et al. 2014). Such sealed units ensure continuous stressor exposure during the experiment and recapture of the study animals following the experiments. However, their small size precludes testing larger animals, or those that require larger living space, and might prevent studying conspecific and interspecific interactions as well as stressor impacts at a community level. As with any enclosure, care must be taken that the enclosure size permits natural behavior and does not impair the health of the study animals. Other disadvantages of offshore studies using mesocosms include logistical complexity and high expense compared to equivalent experiments in the laboratory.

Offshore experiments without mesocosms

Studying impacts of anthropogenic stressors on marine animals in natural conditions without the use of mesocosms is challenging and has only been performed on very few factors such as sedimentation (e.g. Weber et al. 2006) and noise (Brandt et al. 2011, Vabø et al. 2002). Studying impacts of anthropogenic stressors on animals in offshore experiments allows investigations of wild free-ranging animals in their natural environment, including regional environmental physicochemistry. The main disadvantages of offshore studies include the inability to test stressors without permanently contaminating large areas (e.g. when using chemicals) and difficulties in creating future stressor conditions (e.g. when studying ocean acidification or warming) without the use of enclosures. If testing the focal stressor is possible without using an enclosure, it is generally difficult to modify open-water environments in a controlled manner or to control confounding variables during the study, such as nearby human activities or wave action. Continuous tracking of individuals across time can also be compromised due to the spatial area used by the animals of interest. Furthermore, during the stressor experience, free-ranging animals might leave the affected area as a result, eliminating the possibility to investigate long-term stressor exposure and potential habituation.

Novel approach: advantages and disadvantages of shipbuilding docks to study impacts of anthropogenic stressors

A setup that combines the advantages of the controlled environment of a laboratory with an ecologically-relevant large-scale marine arena would be ideal for studying impacts of anthropogenic stressors on marine organisms. In freshwater environments, whole lakes have been used to study impacts of anthropogenic stressors, including eutrophication (Schindler et al. 2008), pharmaceuticals (Kidd et al. 2014) and anthropogenic noise (Jacobsen et al. 2014). Lake experiments have led to substantial advances since they allow for: i) isolation of the stressor of interest and quantification of its impact on wild populations, ii) assessment of ecological risks at the population level, and iii) validation of responses of organisms observed in laboratory experiments with those seen in the field. Moreover, whole lake studies enable the study of entire ecosystems and allow characterization of, for example, natural behavior, pollutant levels, abundance and preferred distributions of organisms prior to and following introduction of the stressor.

Whole environment approaches are generally not feasible in the marine environment. Flooded shipbuilding docks therefore provide a useful potential addition to existing methods. Shipbuilding docks are found around the world, with more than 410 marine shipbuilding docks (>100 m length) currently in operation (Barnes et al. 2006), and many more that are fully functional but not in use. Although docks cannot fully replicate the marine environment, they offer many of the same advantages as whole-lake manipulations. For example, because of their considerable size, shipbuilding docks enable testing of how anthropogenic stressors impact on free-moving animals exhibiting natural behavior, and allow the use of large numbers of animals from a range of interacting species, thus creating experimental ecosystems. Docks can thus generate data on impacts of animal groups under semi-natural conditions, including complex group interactions and interspecific interactions. Docks also enable assessment of how individual impacts may scale up to community-level effects. On a practical level, docks allow complete drainage which greatly facilitates placement and retrieval of equipment (e.g. to position equipment that measures the stressor of interest), ensure good water quality, and enable recapture of all study animals. The main disadvantages of shipbuilding docks compared with offshore setups are the lack of natural environmental variation such as tides, and the absence of a typical coastal benthic ecosystem.

Box 1; suitability of using a shipbuilding dock to study biological impacts of noise

In our case study, we trialed the use of a flooded shipbuilding dock to study impacts of anthropogenic underwater noise on several marine fish species. Underwater noise is an internationally recognized pollutant (e.g. included in the US National Environmental Policy Act) and has been shown to impact a number of fish species (Slabbekoorn Hans et al. 2010). For example, noise exposure in fishes has been shown to increase stress, affect behavior, cause injury and mortality (Bruintjes and Radford 2013, Halvorsen et al. 2012, Hawkins et al. 2014, Simpson et al. 2016, Vabø et al. 2002). Pile driving is commonly used during construction of offshore wind turbines and oil platforms, and generally creates loud and impulsive noise (>200 dB re 1 μPa at source, 1000s of strikes per day). We piloted the use of a former shipbuilding dock to investigate impacts of pile driving on fish behavior. Our particular interest focused on whether pile driving would result in avoidance behavior, changes in swimming speeds, and altered within-species interactions. These measures are particularly difficult to study in many experimental setups, due to the limited possibility to consider natural behavior, the lack of space to test multiple large fishes, the lack of space for an industrial-sized noise source, and general noise-propagation difficulties. As a consequence, there is a general lack of studies that investigate the impact of noise in large water bodies on wild marine animals using realistic anthropogenic noise sources.

The dock used here is located at the Offshore Renewable Energy Catapult centre in Blyth, UK and provides a fully marine experimental arena. Draining and refilling of the dock can be performed within one day (>5 million liters). Dimensions of the dock are 93 x 18 m, with an average water depth of 3 m (range 2.5–3.5 m). The dock incorporated a simulated seabed consisting of sand and small stones from local North Sea sediment (3.5 m deep). At the seaward end of the dock, a section was retained at full depth without sediment (water depth 6.5 m) to facilitate draining. The simulated seabed was held in place by a concrete wall (Fig. 1) and a large net was placed inside the dock (mesh size: 15 mm) to retain study animals within the main simulated seabed section (resulting arena size 81 x 18 x 3 m).

The noise, simulated impulsive impact piling, was generated using a hydraulic post-driver (Wrag Penna200, hammer weight 200 kg) mounted behind a tractor (Fig. 2). A steel pipe (7.5 m length, 16.5 cm diameter, 0.65 cm thickness), with a steel plate (151 x 164 x 1.4 cm) welded 50 cm from the base to ensure a stable pile position during the piling trials, was used as an experimental pile. During trials, the post-driver hammer operated at 10 strikes per minute for a 2-h hour period twice a day for 2.5 successive days (animals were given two days to acclimatize to the dock prior to the noise trials). Sound pressure and particle velocity recordings of the pile-driving operation were made at 10 m intervals at two depths to allow for detailed characterization of the acoustic conditions with and without piling (for details of equipment see Simpson et al. 2016).

Movement patterns of wild-caught Atlantic cod (*Gadus morhua*), black seabream (*Spondyliosoma cantharus*) and plaice (*Pleuronectes platessa*) were assessed during pile driving using small positioning tags (16 x 4 mm; HTI, Seattle, USA) that were programmed to report individual positions every 2.5 s. The results demonstrate increased distance from the noise source during pile-driving exposure, suggesting avoidance, and increased swimming speed, suggesting increased stress levels, for cod and black seabream compared to ambient control conditions (see Fig. 3 for an example track of a cod before and during piling). Nearest-neighbor distance of cod and seabream was not impacted by pile-driving exposure. Plaice, which lack a swim bladder and thus cannot detect acoustic pressure, did not change movement or interactions during pile-driving exposure. (NB: Full details will be presented in Bruintjes *et al*. in prep.)

Using a flooded shipbuilding dock approach made it possible to investigate the impact of a real noise source (pile driving) on commercially important marine fishes. The sound gradient created by the pile driver made it possible to investigate potential avoidance responses of the study animals during exposure, a response that is impossible to study in the laboratory. The results indicate that pile-driving noise results in avoidance behavior by both cod and black seabream, without influencing nearest-neighbor distances.

Moving forward

Here, we present a novel and alternative way to upscale substantially controlled laboratory experiments aimed at studying impacts of anthropogenic stressors on marine animals, without the need to conduct experiments offshore, which might not be possible at all for some stressors.

Our case study described in Box 1 – using a flooded shipbuilding dock to study impacts of a global anthropogenic stressor (noise) on several marine fish species – demonstrates that shipbuilding docks can be used successfully to study multiple wild-caught animals simultaneously and to obtain information concerning: (1) individual and group responses, (2) intraspecific interactions, (3) stressor avoidance, and (4) interspecific differences in reaction to exposure of the same stressor. The dock results are not easily obtained in small setups due to the typical challenge of keeping groups of fishes in small spaces without impairing natural behavior, and the difficulty of creating a realistic stressor gradient. Moreover, such results are challenging to obtain offshore using mesocosms due to complicated logistics and lack of controlled experimental conditions, while studying impacts of anthropogenic stressors on free-ranging animals offshore without the use of mesocosms causes difficulties in tracking animals individually and thus obtaining information on individual and group interactions.

We suggest that not only noise, but also impacts of other important anthropogenic stressors could be tested using a dock setup, including stressors that cannot be easily investigated offshore. For example, ocean warming could be studied through the use of (multiple) heating devices; such studies could create a temperature-gradient that could give essential information concerning preferred temperatures during various life stages, as well as impacts on free-moving animals during or following warming (Table 2). Additional anthropogenic stressors that could be studied using a dock approach, including unique opportunities and suggestions on how to perform the specific manipulations and corresponding challenges, are listed in Table 2.

Moving forward, dock setups could help answer questions concerning the impacts of anthropogenic stressors at a community level through creating and studying mini-ecosystems inside the dock. Dock setups allow studying simultaneous large-scale and long-term exposure of stressors and their impact on free-moving marine animals, providing invaluable data concerning stressor impacts at environmentally relevant exposure levels and predicted future stressor levels. Such results provide essential parameters for predictive models on population, community and ecosystem level impacts. Statistical and mechanistic models have been successfully developed to predict biological responses to a range of environmental stressors, for example, species distributional changes due to ocean warming (Cheung et al. 2009) and acidification (Le Quesne and Pinnegar 2012), but these models are typically limited by a lack of accurate or realistic data for the species or stressor of interest. Ultimately, predictive models could help to assess current and future ecological risks and, although this might be complicated, help to facilitate appropriate management and develop suitable mitigation strategies.

Conclusion

Flooded shipbuilding docks could be a useful addition to the existing repertoire of methods used to study impacts of stressors on marine animals, especially since the approach allows investigations of anthropogenic stressors that are currently challenging to test in large-scale experiments. The dock approach overcomes many issues of laboratory-based and offshore experiments and permits tight experimental control whilst allowing for control of many of the confounding factors that operate in natural systems.

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369 Figure 1.

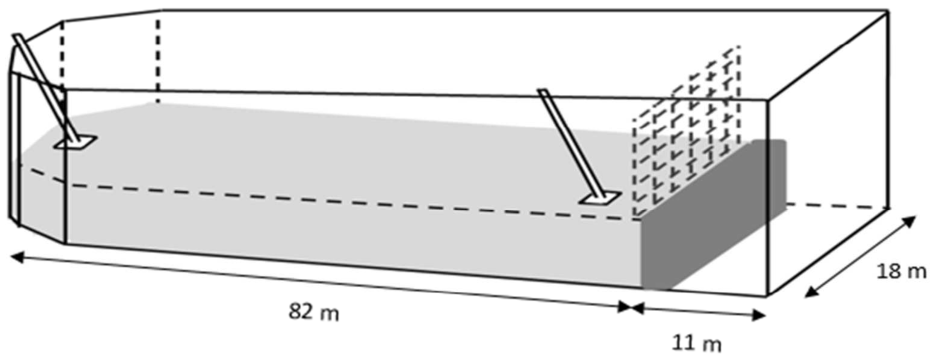

Figure 1: Schematic representation of the shipbuilding dock with the simulated seabed (light grey), the wall holding the seabed in place (dark grey), two piles, and the net keeping the animals in the simulated seabed section (the dashed parallelogram). The section lacking sediment at the right side was necessary for water drainage.

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Figure 2.

Figure 2. The post-driver and pile set up.

Figure 3.

a. b.

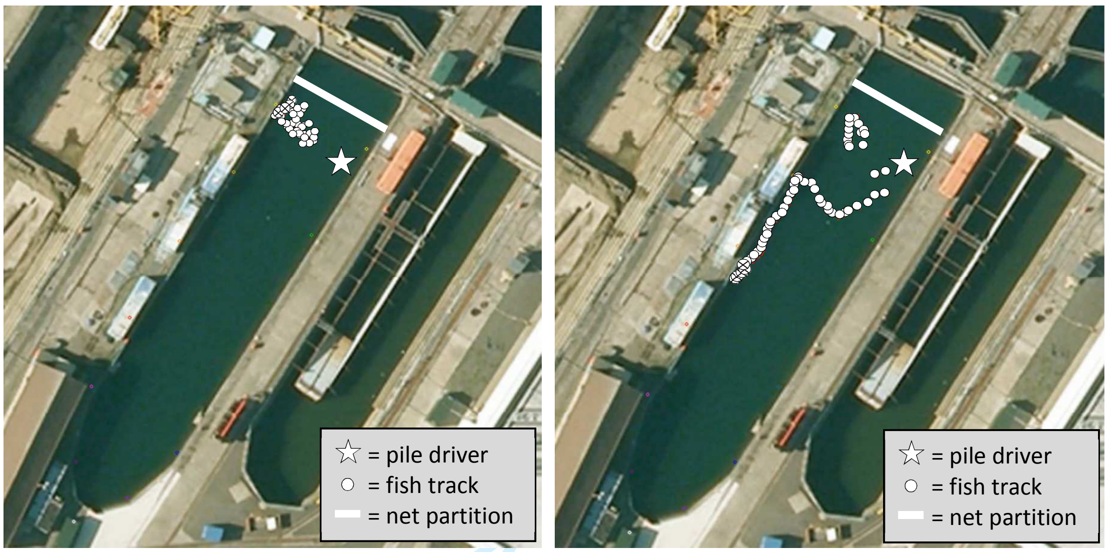

Figure 3. Aerial view of the dock with (a) the swim track (white dots) of a naïve cod during the five minutes prior to pile driving (ambient control), and (b) the swim track of the same fish during the first five minutes of pile driving. The white dots encircling an ‘x’ depict the last five time steps (base image from Google Maps).

Table legends

Table 1. Merits and limitations of studying impacts of anthropogenic stressors on marine animals using aquaria in laboratory settings, shipbuilding docks and offshore setups (divided into offshore using mesocosm [a structure that retains focal animals in one location] and offshore using free ranging animals). ✓✓ = high agreement, ✓ = medium agreement, **-** = no agreement nor disagreement, ✗ = medium disagreement, ✗✗ = high disagreement.

Table 2. Examples of anthropogenic stressors that could be studied using a shipbuilding dock setup including their opportunities, how to perform the manipulations and challenges. Stressors (in italic) are arranged in the following categories: global change, chemical, ecological and multiple stressors (in bold).

Table 1.

		Aquarium[1]	Ship-building dock	Offshore (meso-cosm)[2]	Offshore (free ranging)
General experimental considerations	Explore potential future impact stressor	✓✓	✓✓	✓✓	✗✗
	Test stressor on a large scale	✗✗	✓	✓	✓✓
	Use free moving animals	–	✓	✓	✓✓
	Natural behaviour	–	✓	✓	✓✓
	Environmental complexity	✗✗	–	✓	✓✓
	Controlled experimental conditions	✓✓	✓	✗	✗✗
	Chronic exposure studies	✓✓	✓✓	✓✓	✗✗
	Ecosystem/community level experiments	✗	✓	✓	✓✓
	Long-term experiments	✓✓	✓	✓	✗✗
	Reality stressor experience	–	✓	✓✓	✓✓
	Stable stressor concentration/quantity (e.g. chemical compound, noise)	✓	✓	✗	✗✗
	Subjects only exposed to the stressor of interest	✓✓	✓✓	✗✗	✗✗
	Natural habitat (e.g. tides, food, water quality)	✗✗	–	✓	✓✓
	Ease of logistics (e.g. setup time, resource availability)	✓✓	–	✗	✗✗
	Test large organisms or those that need a large living space	✗✗	✓	✓	✓✓
	Ease of tracking individuals	✓✓	✓	✓	✗✗
	Straightforward real-time measuring	✓✓	✓	✗	✗✗
	Low cost	✓✓	✓	✗	✗✗
	Site security	✓✓	✓	✗✗	✗✗
Sound-specific experiments considerations	Use of real noise sources	✗	✓	✓	✓✓
	Sound propagation quality	✗✗	✓	✓✓	✓✓
	Natural sound pressure and particle motion levels	✗	✓	✓	✓

[1]A 200 l aquarium example was used for comparison.

[2]A 20 x 20 x 2 m cage-like structure, i.e. allowing water flow but retaining focal animals, was used for comparison.

Table 2.		Opportunities	How to perform manipulation	Challenges
Global Change stressors	*Ocean warming*	Gradient establishment (to study preferred temperatures)	Dock water temperature can be increased using heaters	Numerous heaters and high energy requirement
	Acidification	Gradient establishment	Dock water can be acidified using continuous CO_2 injections	-Large CO_2 quantities needed -CO_2 exchange with atmosphere reduces levels
	Salinity	From fresh water to hypersaline	Modify dock water salinity using fresh water or salt	Establishing large quantities of water with certain salinity
	Low dissolved oxygen levels (hypoxia)	Gradient establishment	Low dissolved oxygen levels through continuous N_2/air mixture injections	Use of chemicals to drop oxygen levels
	Sedimentation	Gradient establishment	Sedimentation can be simulated through addition of e.g. fine sand.	Large sedimentation quantities needed; sedimentation addition issues
Chemical stressors	*Chemicals (including pharmaceuticals)*	-Gradient establishment -Possibility to study impact of water-soluble and non-soluble chemicals	Contaminate dock water and/or the dock sediment using (biodegradable) chemicals or pharmaceuticals	Non- and slow-biodegradable chemicals need filtering out following experiments, which might be difficult and costly
	Eutrophication	Establishment of a gradient	Dock water nutrient levels can be enriched using fertilizer or phosphates	Large quantities of fertilizer needed
Ecological stressors	*Light*	-Gradient establishment -Studies on e.g. avoidance and bio-rhythm impact -Use of submerged and non-submerged light	Dock water can be lit using aerial or submersible floodlights	Powerful lights required
	Invasive species	-Impacts of invasive species on local animals or communities -Identification of vulnerable life stages	Introduce invasive species	-Transport of invasive species to the site -removal of invasive species to avoid subsequent release
	Noise	Gradient establishment	Use a noise source inside the dock (e.g. a pile driver [Fig. 3] or airgun; see Box 1 for a noise experiment in a shipbuilding dock)	Construction of proper noise source
Multiple stressors	*Combination of stressors*	Collection of data on the impacts of multiple polluters simultaneously	Use different combinations of anthropogenic stressors	Simultaneous exposure of the study objects to both stressors